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Detectors requirements for the ODIN beamline at ESS

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Abstract

The upcoming high intensity pulsed spallation neutron source ESS, now in construction in Sweden, will provide unprecedented opportunities for neutron science worldwide. In particular, neutron imaging will benefit from the time structure of the source and its high brilliance. These features will unlock new opportunities at the imaging beamline ODIN, but only if suitable detectors are employed and, in some cases, upgraded. In this paper, we highlight the current state-of-the-art for neutron imaging detectors, pointing out that, while no single presently existing detector can fulfill all the requirements currently needed to exploit the source to its limits, the wide range of applications of ODIN can be successfully covered by a suite of current state-of-the-art detectors. Furthermore we speculate on improvements to the current detector technologies that would expand the range of the existing detectors and application range and we outline a strategy to have the best possible combined system for the foreseen day 1 operations of ODIN in 2019.

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1. Introduction

ESS will feature a higher intensity per pulse than that of any other pulsed source worldwide, and the time integrated flux will be of the order of that of ILL [1], for cold neutrons maybe even beyond. This will unlock new possibilities in neutron science in general and in neutron imaging in particular [2] [3] [4]. The Optical and Diffraction Imaging with Neutrons (ODIN) instrument [4] [5] is one of the instruments foreseen to produce data from day-1 of operations scheduled for 2019. Already, the outstanding time-averaged flux should allow improvements on the state-of-the-art techniques in neutron imaging, but the pulsed structure will enable energy selective techniques with unprecedented resolution and flexibility. To exploit all the potential

of such a promising source, suitable detectors must be employed. In this document we report the current state-of-the-art in imaging detectors and an outlook for the near future with regards to the foreseeable requirements of an instrument like ODIN.

2. Imaging at ESS

With the high flux and the tunable time structure that will be featured at ODIN [4] [5], many new possibilities will open for neutron imaging. To profit fully from these perks, and given that in neutron imaging it is customary to change detector depending on specific experimental conditions and requirements, a suitable set of detectors will need to be available on demand.

The main characteristics of ODIN that need to be exploited with a suitable choice of detectors are:

- 1- A large field of view (FoV) (up to $25 \times 25 \text{ cm}^2$) that allows imaging of large objects, for example, for industrial applications including kinetic measurements and cultural heritage
- 2- The intense beam that enables high resolution imaging, needed when investigating samples with small features (of the order of tens of microns and below)
- 3- as well as fast kinetics (tens of milliseconds range) or an adapted stroboscopic mode for repetitive processes (down to microsecond range)
- 4- The (tunable) time structure of the neutron pulse, for which time-of-flight (ToF) mode down to microsecond time resolution capabilities of the detectors are required to achieve the highest neutron energy resolution regime foreseen

At present, there is no single detector that can fulfill all these requirements at the same time, but it is possible, instead, to choose a detector that fulfills very well two of them, complementing each other sufficiently for any applications currently envisaged.

- 1- Scintillator-Camera detectors have a big (and tunable) FoV and can achieve best spatial resolution. They are currently best suited to fulfill the requirements in 1- and 2-, partly even 3-, above. They are hence standard and continuously further developed in terms of efficiency and spatial resolution at state-of-the-art continuous source instruments.
- 2- Special MCP-based detectors [6] have a high temporal and spatial resolution on a relatively small FoV, and can cover most applications summarized in points 3- and 4- above, partly also in point 2- when related to high spatial resolution in small samples. They are currently the most exploited choice for ToF imaging applications.
- 3- Wire chamber detectors have a big field of view and good timing capabilities but low spatial resolution. They are currently mainly applied in scattering but might hold potential for some novel ToF imaging modes very well suited at ODIN, in the case that high spatial resolution has low priority in contrast to good ToF resolution on a large FoV.
- 4- Other technologies exist or are in development, mostly following similar trends toward higher spatial and/or time resolution. More dedicated detectors are foreseen to build up a stock at ODIN for very specific experimental needs, such as extremely high spatial resolution imaging and very fast stroboscopic and kinetic imaging.

In the following, the state-of-the-art in applied detector technology for neutron imaging as well as the specific strategy required for ODIN to be equipped with suitable detectors will be discussed in detail. Further requirements for imaging detectors, apart from the highest level ones as discussed above like high spatial resolution, temporal resolution and including dynamic range, count rate capabilities, radiation hardness, gamma sensitivity, stability (long time stability) etc. will be discussed along the lines where one or more of these requirements are of concern with a specific technology.

3. State-of-the-art

3.1 Analog and hybrid analog-digital detectors

Historically neutron imaging was performed in an analog way by means of neutron-sensitive emulsions requiring chemical processing after exposure. A bridge to the digital world was later made by the use of imaging plates digitally read by a scanner [7]. These plates exploit photostimulated luminescence by a phosphor excited by a neutron-sensitive medium to record a signal proportional to the neutron irradiation. However, the read-out process of such plates is relatively cumbersome as it can take minutes to digitally read out a film. This technology still exists and features relatively high spatial resolution (below 100 μm) for a large area (up to 40 x 40 cm^2). It is situationally useful for particular applications such as single shots at high resolution of large objects and, given that the thickness of these imaging plates is of the order of 2 cm, an advantage when space considerations along the beam are important (for instance, when checking the beam profile between guide sections). There exist particular emulsions which can also operate discrimination between gammas and neutron [8], which can be advantageous at times. However, this technology cannot be seen as a state-of-the-art for wide applications in neutron imaging nowadays and hence not as a primary choice.

3.2 Flat panel detector

A more modern version of compact detectors is the flat panel detector, adapted from medical X-ray imaging. It consists of an amorphous silicon panel sensitive to the light produced by an adjacent suitable neutron scintillator [9], with the added advantage of being extremely radiation-resistant. This technology has the same advantage in terms of the space considerations as the imaging plates, but it is read digitally with a frequency up to about 20 Hz. So far, it has not been extensively used because of the fixed and relatively coarse achievable resolution (normally around 200 μm), but models with pixel sizes as small as 50 μm exist now). It might become more and more viable as the technology progresses, in particular again as its outer dimensions constitute certain advantages concerning detector set-up and change. Nevertheless, with the lack in flexibility as compared to state-of-the-art systems it is not a current priority choice for ODIN.

3.3 Camera and scintillator systems

Presently the vast majority of imaging experiments is performed with a system of a camera and scintillator (Fig. 1).

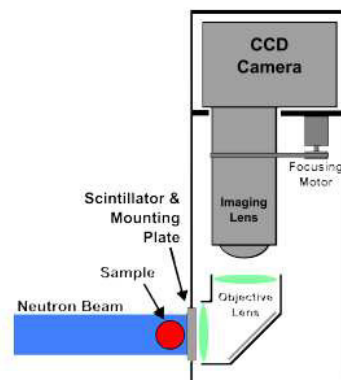


Fig. 1: Schematics of the setup for neutron imaging with a scintillator and camera based detection system. [10]

The camera is an optical camera which must be extremely sensitive to a very low level of illumination and able to integrate this low intensity over a relatively long time. The scintillator is usually a tertiary compound composed of a phosphor (producing light), a molecule containing large cross-section elements for the actual capture of the neutron (usually Gd, B or Li) and a binder for mechanical stability. Alternatives exist to this general design, most prominently the scintillators based on gadolinium oxysulfide which is a phosphor in itself and contains also the element for efficient neutron capture (Gd). In most other cases, the phosphor used is ZnS:Cu,Al for its strong emission at green wavelength, where cameras are most sensitive.

Most of the time, cameras are based on CCD technologies, even though the most recent advances brought scientific CMOS-based cameras on equal grounds with CCDs. In comparison to CCD-based cameras, sCMOS trade relatively less stability at low-illumination levels for a much higher frame rate and wider dynamic range.

The standard chip size for regular imaging is currently 1k x 1k, even though 2k x 2k cameras are becoming more and more common, and 4k x 4k cameras are already on the market (in particular from astronomy applications).

The advantages of camera-based detectors are numerous, in particular the tunable field of view and pixel size thanks to dedicated (light) optics attached to the camera itself. On demand, and given suitable infrastructure, the field of view can vary from larger than 25 x 25 cm² to a few square centimeters, with corresponding increase in resolution. At present, the best achieved performance for neutron imaging was of the order of 10 μ m real resolution (i.e. not pixel size), even though advancements are being pursued with dedicated optics [10] [11]. At this small pixel size, the flux is becoming more and more the ultimately limiting factor, because there are too few neutrons per pixels per second to yield an image in a reasonable amount of time. But also the capture probability of scintillators decreases for the layer thicknesses required to achieve such high spatial accuracy. Given the high flux, ESS is the best suited source for pushing this boundary even further, reaching the small single-digit micron resolution for conventional neutron imaging.

Given the underlying process of light emission, scintillators are best suited for steady-state imaging. The onset time for the light emission and the afterglow of the phosphor in fact, severely limit the achievable time resolution needed for ToF imaging, just as much as required read-out times of the CCDs and the associated readout noise. However, fast scintillators have been developed for this purpose [12].

For ToF applications, dedicated cameras are needed to exploit the time structure of the pulsed source. Such a camera should have a very low exposure time repeated all over the pulse duration, in order to be synchronized with a particular ToF. Since a single pulse would not be enough to exploit a reasonable dynamic range, a stroboscopic operation mode could be used to register high ToF resolved images and accumulate them over several pulses in the correct order, indexed by the correct ToF. So far, the available technology for such cameras (Image Signal Acquisition Sensor) [13] is very rarely used in neutron imaging because it features an unsatisfactory number of pixels [14] and would hence also not meet the requirements of ODIN in terms of resolution and/or FoV. Developments in this field are foreseeable, in particular with a close contact with the manufacturers and having the upcoming imaging facilities at pulsed spallation neutron sources [14] [15] [16] as the driving force for corresponding upgrades.

However, already existing technology for ToF-resolved imaging is available and does not rely on conventional camera-scintillator pairs. These have hence higher priority for ODIN and will be discussed below.

3.4 Scattering detectors

2D detectors exploited in neutron scattering can potentially be employed for very coarse imaging resolution. Detector types such as delay-line based ³He wire chambers [17] [18] can have a spatial resolution of the order of 1mm and a time resolution as low as 1ns, providing very basic imaging capabilities over large fields of view (i.e. 20 x 20 cm² and more) while still being able to record the ToF of each single neutron. This kind of detectors features also an inherently low gamma sensitivity coupled with a high neutron cross section.

The downsides are the aforementioned poor spatial resolution and the limited counting rate that they can withstand (of the order of 100k cps), coming from the electronics that controls the correct attribution of the ToF to each captured neutron and corresponding deadtimes. With better and more robust electronics, improvements in the spatial resolution are foreseeable. Incidentally, a closer packing of the wires would also improve at least the local counting rate capabilities, since fewer neutrons per pixel will hit the detector, lowering the risk of event overlap. Developments in this area are however ongoing for all kinds of scattering instruments in particular for high flux pulsed sources like the ESS. Such detectors could become interesting to complement a state-of-the-art imaging detector suite at ODIN.

3.5 MCP-based detectors

At the other end of the spectrum, there is the currently available baseline detector for high-resolution ToF imaging: the MCP based neutron counting detector [6]. It consists of one 10B-doped microchannel plate (standard 33mm diameter) with pores (microchannels) of the order of 10 μm and an intrinsic L/D of the order of 100:1 (Fig. 2). It is followed by a stack of two standard glass MCPs and a Medipix2 readout placed 0.7 mm behind the MCP stack. This combination can detect and store full frames at frequencies in excess of 100 kHz with a spatial (pixel) resolution of 55 μm . If a higher resolution is needed, this detector can operate in centroiding mode, where it calculates in real time the centroid of the detected electron cloud following a neutron capture. However, this severely reduces the accepted flux and in particular the timing resolution, but increases the spatial resolution to $< 15 \mu\text{m}$. This particular high spatial resolution mode is hence not suited for ToF. The detection efficiency of such a system is relatively high (but not as high as e.g. wire-chamber detectors), being of the order of more than 40% for a cold neutron beam [6] and does not show a particularly strong gamma sensitivity. Even measurements during unattenuated prompt pulses at state-of-the-art pulsed spallation sources have proven to be feasible, so it can be expected that in the long term this will limit the detector lifetime severely.

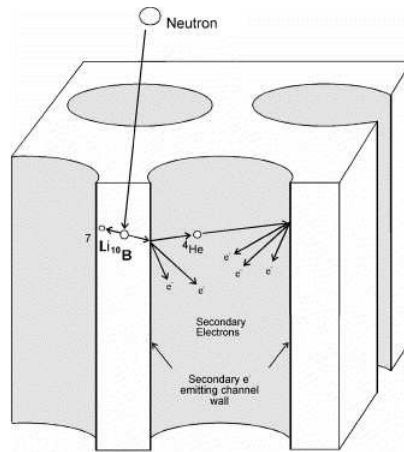


Fig. 2: Detection mechanism of the MCP-based detectors [19].

This type of detectors is the best candidate to fulfill all the conditions and to exploit the advantages of ESS pulsed source for ToF imaging. The main drawback of this detector is the very limited FoV (about $2.8 \times 2.8 \text{ cm}^2$), which should be overcome, if such a detector is to cover all ToF applications ODIN potentially provides. However, with the availability of the new versions of medipix/timepix3, some of the key parameters are still expected to improve within the near future (approximately 2 years), such as count rate capability and FoV. Currently, corrections are available to be applied for the deadtime at very high ToF flux ($> 10^7 \text{ cm}^{-2} \text{ s}^{-1}$) and short interruptions for read-out during each pulse are introduced (custom defined parts of

wavelength frame). Even though this is a slight drawback, it does not compromise the performance of this leading technology for ToF imaging more than acceptable for currently known applications.

4. Requirements of ODIN (for day 1 and beyond)

The detector suite for the day 1 operation of ODIN can be set with respect to the current state-of-the-art at this stage. It provides a safe solution to fulfill the main requirements of the new imaging beamline even with state-of-the-art solutions and hence without relying on future technological developments, because the basic operations can be guaranteed with already existing detectors.

Three main modes of operation e.g. for white beam imaging, concerning FoV are envisaged, depending on the sample size: large samples (FOV bigger than $25 \times 25 \text{ cm}^2$), medium-sized samples (between $25 \times 25 \text{ cm}^2$ and $5 \times 5 \text{ cm}^2$) and small samples (below $5 \times 5 \text{ cm}^2$). The corresponding expected resolutions are, respectively, 200-300 μm , 50-150 μm and $\leq 10 \text{ }\mu\text{m}$. This range can comfortably be filled with a set of 2-3 cameras (most likely a combination of CCD and sCMOS) with up to 4MPixels chips and a set of 3-4 objectives. While the traditional domain of the CMOS is mainly for kinetic applications, new technology also qualifies cameras for certain steady state imaging. Several scintillator screens of different size and thickness (trading efficiency against resolution) will also be needed for each combination. Improvements in the technology will translate directly into improvements in the image quality, but it is not expected that these combination will be replaced by any other technology in the near future for such applications.

Particular care should be taken when aiming for resolutions of 10 μm or even better. In such cases (and in the latter in particular) dedicated optics are sometimes required. The design of these could be based on currently available designs at state-of-the-art imaging beamlines [10] [11]. Own development in this direction is not carried out at ESS for day 1 operation of ODIN. However, dedicated developments are ongoing elsewhere [11]. An adaptation of results for ODIN will be considered.

For ToF applications with sufficient spatial imaging resolution, at least one MCP-based detector, or comparable technology established until 2019, has to be available as day-1 equipment.

At least one counting detector will most likely, from today's point of view, be needed to complement the day-1 instrument detector suite.

5. Strategy

Several possible (and desirable) improvements can be foreseen to tailor detector capabilities to the specific characteristic of ESS and ODIN for specific applications. Such improvements, however, appear currently feasible and achievable within the timeframe of ESS construction and certainly operation. However, some actions are required in order to stimulate suitable developments because, without an external driving force, the market for these applications is very limited and the requests are very specific. A particular advantage is, however, that the imaging beamlines at JPARC [14] and ISIS [15] are or become operational in 2015 and have already stimulated corresponding developments, which have to be observed closely in order to choose the best state-of-the-art solutions for ODIN around about 2017/18 along the lines described above.

5.1 Analog and hybrid analog-digital detectors

For the analog methods option (imaging plates), not many improvements can be expected, and it must be decided whether to put any emphasis on developments in this direction at all. Current thinking is that such solutions might be interesting additions to a core detector suite in the future but not for initial operation and the core scope of the instrument.

5.2 Flat panel detector

Amorphous silicon flat panels are, at the moment, nearly not used in neutron imaging facilities, but as the electronics get faster and faster, it is not inconceivable that they will become competitors for camera-based detectors. Their robustness to radiation (in the direct beam), their compactness and their size are obvious advantages, but some improvements are required to decrease the pixel size to bring it to the same required range as for camera-based detectors. The driving electronics, now sometimes immediately behind the active area, should also be moved spatially in the design, where it can be shielded properly to avoid damage, just like cameras are moved out of the line of sight and can be heavily shielded for these reasons in scintillator/camera detectors. Any intention for such a detection system to be in the initial detector suite of ODIN would require a strong and timely collaboration with some manufacturers but both are currently not foreseen.

5.3 Camera and scintillator systems

Concerning camera-based detectors, two different approaches must be distinguished and analyzed separately: white beam and ToF imaging.

For the standard white beam case, the scintillator / camera pair is a solid one that will be part of the day 1 detector suite of ODIN. On the camera side, improvements can still be significant but are not critical for the moment and for day 1 operations, such as: smaller pixels for higher resolution, bigger chips with more pixels for higher resolution imaging of large samples or chips with lower sensitivity to gamma radiation. 1MPixels cameras and 4MPixels cameras should be the default options, with 16MPixels camera to be considered. The scintillator is probably the most improvable element of the pair. More stability, faster decay of the afterglow and onset of the luminescence are desirable and, with careful engineering, achievable within years. The critical factor might be potential efficiency losses related to this. For the very high resolution case, i.e. down to the micrometer range, the situation is more delicate but projects are already on their way and they should yield the first results in the near future. Day 1 detector solutions for white beam imaging should take these improvements in technology into account for several different use cases such as (i) large field of view, low to medium spatial resolution imaging, (ii) highest spatial resolution imaging on medium to low FoV sizes and (iii) time resolved (kinetic) studies down to about 10 millisecc time resolution as well as stroboscopic kinetic studies with down to microsecond resolution on medium to large FoV sizes with relaxed spatial resolution. All developments in this field are strongly driven by existing state-of-the-art facilities and do not require additional stimulation.

For ToF imaging with a camera, besides observing closely the progress made for other ToF imaging facilities starting operation in 2014/15 and building upon such developments, some contacts with respective manufacturer companies could be commenced in the very near future. The task of developing a gated chip able to store sub-frames indexed by the ToF in a pulse appears to be feasible, but did not yet lead to convincing results for the aforementioned facilities. Improvement in the scintillator material will also be beneficial for this branch, providing screens that react as promptly as possible to external stimuli. However, also the high readout noise of camera systems as compared to event counting devices is also a severe handicap for potential time-of-flight applications. The current situation and progress does not qualify such solutions for ToF applications at ODIN, but if corresponding approaches demonstrate improvements and feasibility at other projects, options for day-1 solutions might arise. The current strategy is observation of such development to judge the progress. A maximum stimulus and input of ideas is foreseen for corresponding developments. However, as such systems are expected to cover ToF resolution at best for low energy resolutions, though on large FOVs, such systems have no promise so far to cover a broad application range and hence would at best qualify as an additional but not core system at some given time significantly after day 1.

5.4 Scattering detectors

For complementing ODIN beamline with scattering detection capabilities and for very low spatial resolution ToF applications on a large FoV, the current existing 2D delay-line based ^3He wire chambers are already a good choice. If they are to be more focused on imaging, however, they should be improved in terms of resolution (an order of magnitude more would be ideal) and count rate capability. These improvements should be possible, but must be pursued as soon as possible. The ODIN project here relies on the ESS scattering instrument suite for corresponding stimulation of development and is observing a few projects with increased attention.

5.5 MCP-based and other novel ToF imaging detector technology

MCP-based detectors are currently the obvious choice for being the main ToF detectors at ODIN. Close scientific collaborations and contacts are established with the developers. Main additional requirements are towards the feasibility of larger FoV detectors, but also higher flux conditions, which might be solved by the Timepix 3 technology currently introduced. Bigger FoV even at the expense of the maximum resolution would extend their application range to mid-resolution ToF imaging. However, there are currently several additional projects on the way that are developing potentially well suited detectors for such applications [20] [21] including those aiming to exploit timepix technology as well [22]. The instrument team is largely involved and at least closely observing such developments, which will most likely be tested first at earlier ToF imaging beamlines before ODIN becomes operational.

5.6 Computation

A last consideration should go to the computational power needed to store and process the large amount of data resulting from a ToF imaging facility. Imaging is, by itself, a computationally- and memory-intensive business, and requires dedicated hardware configurations. A worst case scenario could be fast full time-of-flight-resolved tomography. This will be a 4-dimensional dataset with a size of the order of $> 0.5\text{TB}$ of raw data produced on a timescale of minutes to a few hours. Only the transfer and the storage of this amount of data will present challenges that must be taken into account when highlighting the basic requirements for the detectors at ODIN. The processing of these data, is another big challenge, but will not be discussed here.

6. Conclusions

Available detectors for neutron imaging are already a safe solution for the basic requirements of a future ODIN instrument: they can definitely be improved, but already the present state-of-the-art would potentially make ODIN the best and in particular most flexible neutron imaging instrument worldwide. Core improvements in the state-of-the-art desired to improve the coverage of ODIN requirements seem feasible and achievable within the time scale of ODIN construction. With ESS as a driving force, swift actions are required should be put in place to involve manufacturers/developers of current state-of-the-art and novel technology to push the limits even further. The direction to take and the requirements are clear and are not an impediment to the successful usage of ODIN as day-1 ESS instrument in 2019.

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